SciDAC 09 Review : PWFA

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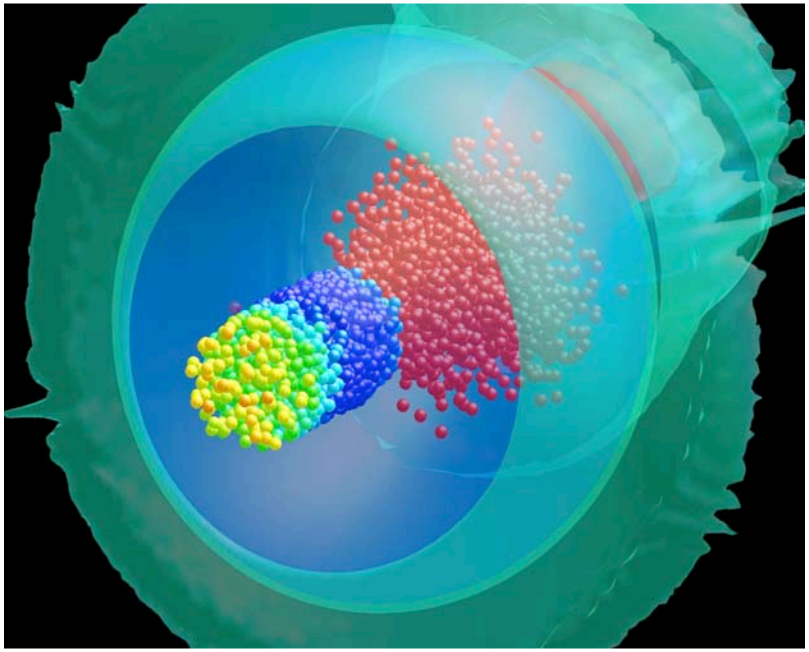
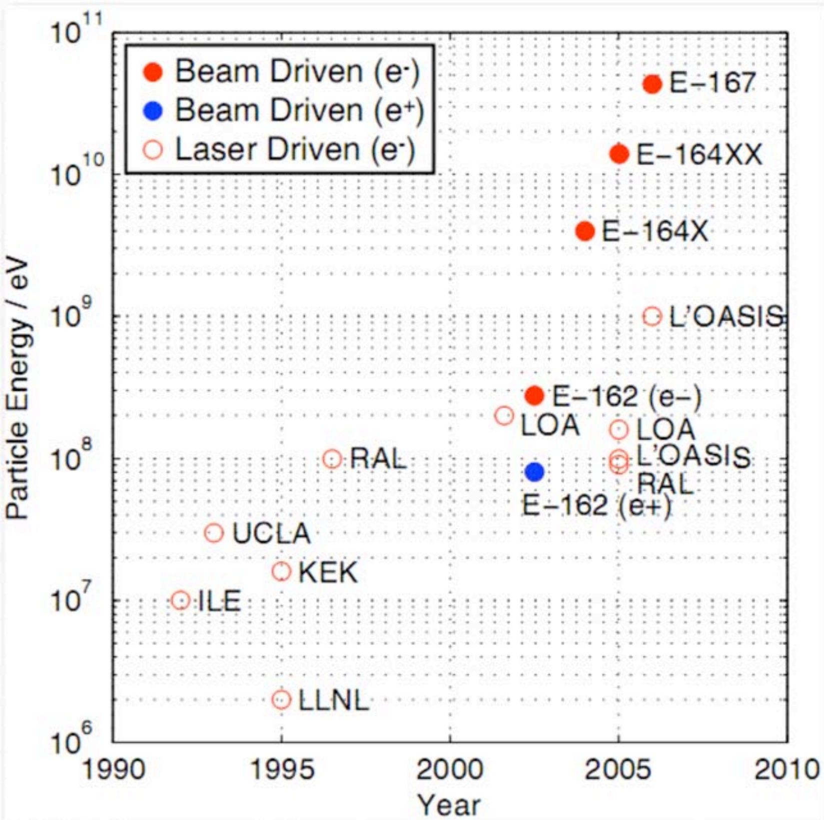
W. Lu, Weiming An, W. B. Mori, T. Katsouleas,
M. Tzoufras, S. Martins, M. M. Zhou, M. Hogan,
plus members of the FACET team.

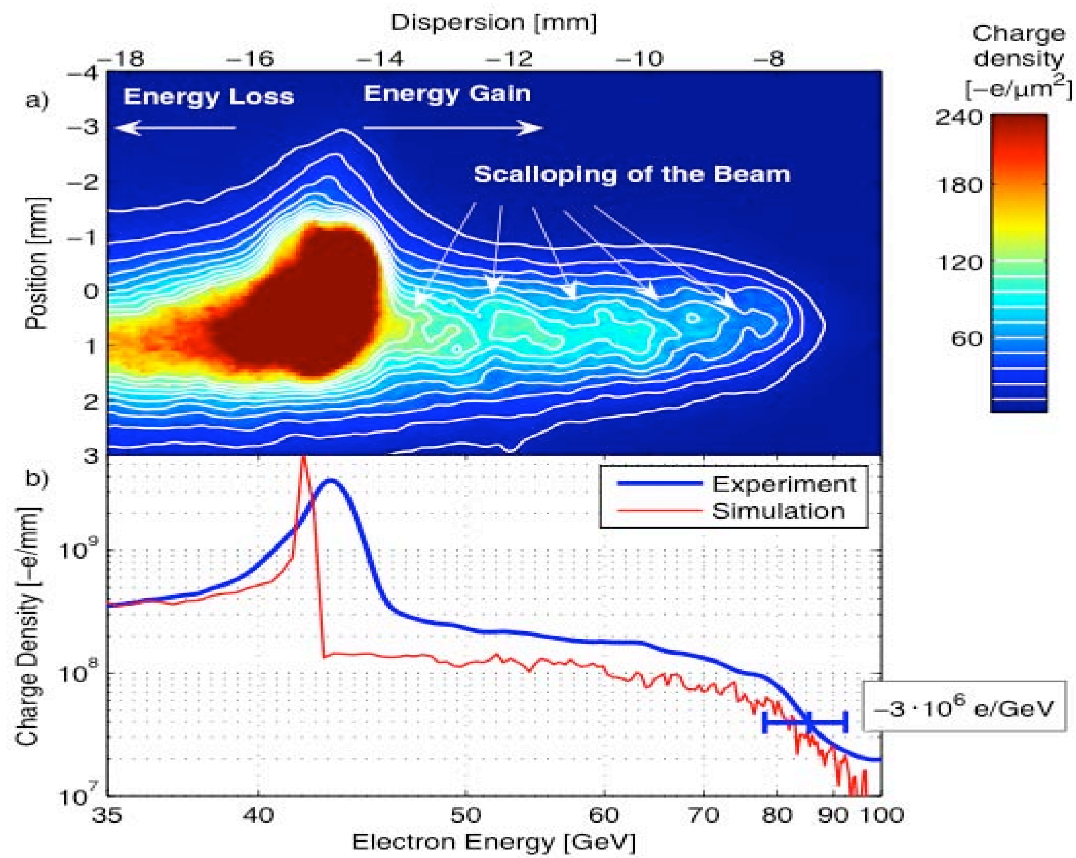


UCLA SLAC USC Duke UNIVERSITY

PWFA as energy doubler



The Energy Doubling Experiment



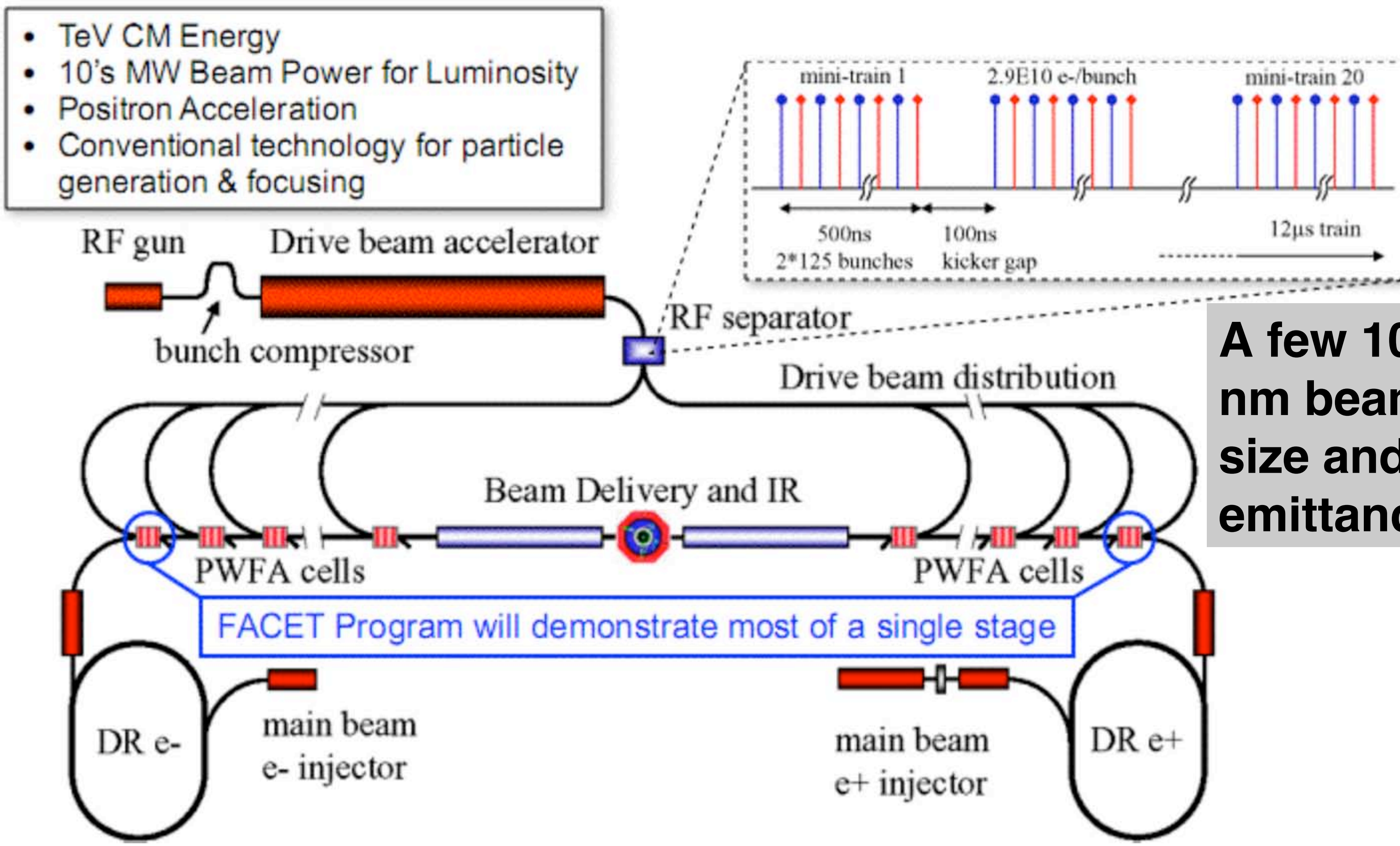
Blumenfeld et. al. Nature (2007)

Accelerated particles are in tail of beam.
Next step: demonstrate high quality beam acceleration

$$42\,GeV, N_b = 1.7\times10^{10}, \sigma_r = 10\,\mu m$$

$$\sigma_z = 15\,\mu m, n_p = 2.7\times10^{17}\,cm^{-3}$$

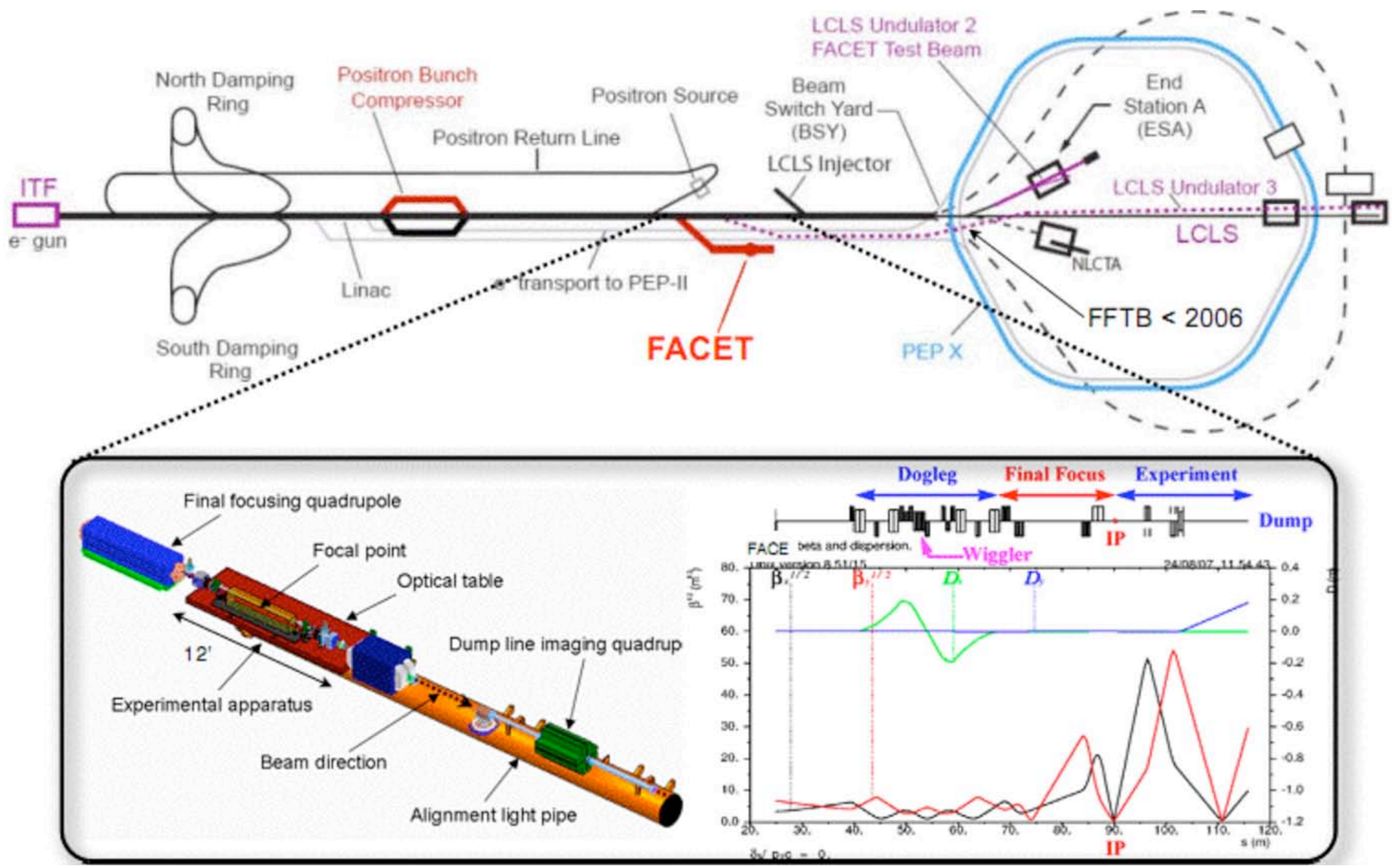
PWFA-based collider concept



A few 10s nm beam size and emittance

a 19 Stages PWFA-LC with 25GeV energy gain per stage

Facilities for ACcelerator science and Experimental Test Beams

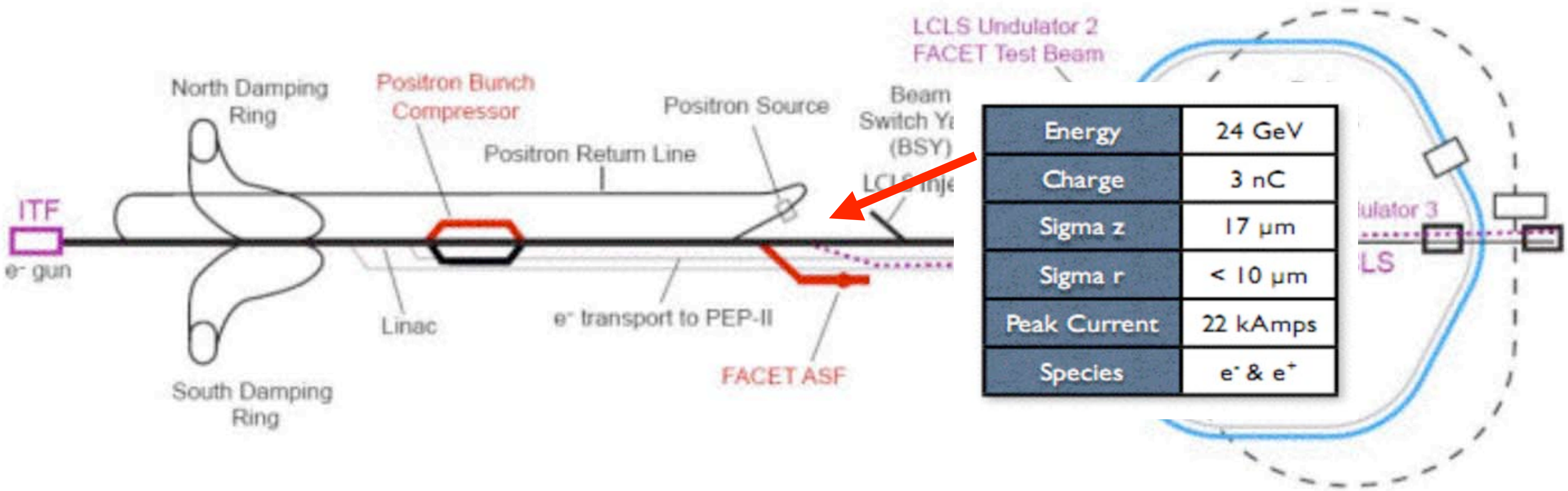


FACET is a new facility to provide high-energy, high peak current e^- & e^+ beams for PWFA experiments at SLAC

PWFA research @ FACET

The PWFA-LC concept illustrates the key questions that must be answered:

* High beam loading with both electrons and positrons (required for high efficiency)
* Small energy spreads (required to achieve luminosity and luminosity spectrum),
* Small emittances and small emittance dilution (required to achieve luminosity),
* Average bunch repetition rates in the 10's of kHz (required to achieve luminosity)
* Multiple plasma stages to achieve the desired energy.



Energy	24 GeV
Charge	3 nC
Sigma z	17 μm
Sigma r	< 10 μm
Peak Current	22 kAmps
Species	e^- & e^+

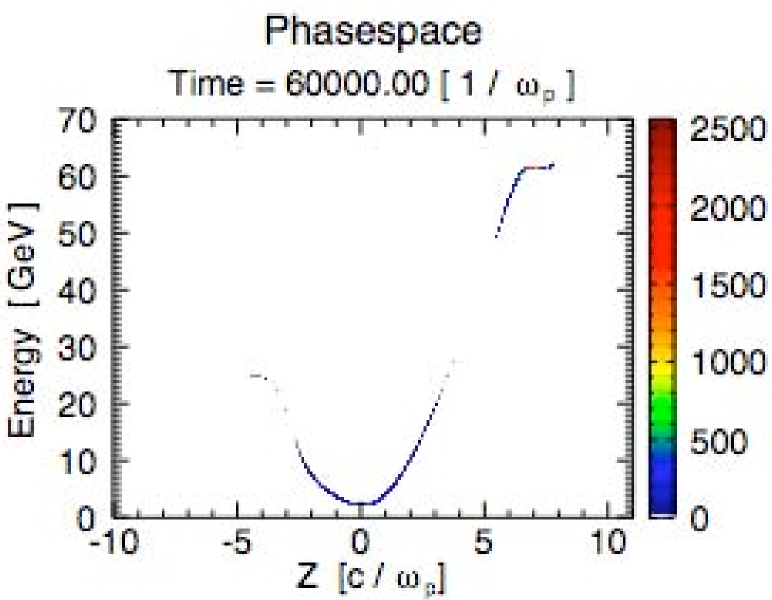
Plasma Acceleration Research Program at FACET will focus on the first three

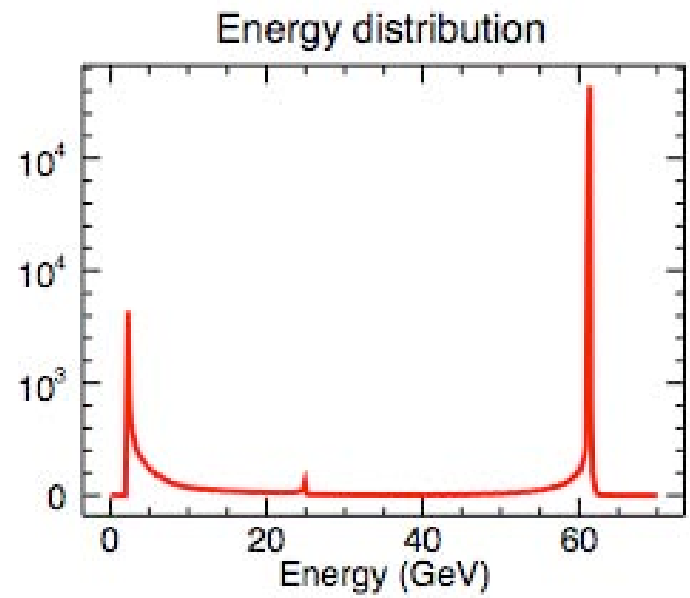
Simulation needs

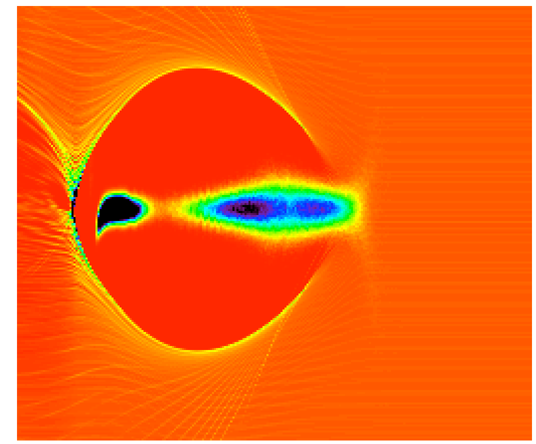
- Propagation in meter long plasma + highly relativistic beam provides clear separation of time scales, well suited for reduced PIC code.
- 3D effects such as hosing and asymmetric beam sizes are important, 3D simulation model required.
- Spot sizes are extremely tight for a electron positron collider, the transverse resolution has to be extremely high which means very strict time step requirement for a full PIC model.
- For example, beam size in next linear collider is 600x6 nm^2, simulation box size is 200x200 micron^2, needs 600x60000x500 grids, time step < 0.7 fs, # of time step ~ 1E7 for one 25 GeV stage.

Quasi-static PIC model appears to be only choice for full physics modeling of PWFA-LC. Full PIC for short distances allows model validation.

Nominal 25 GeV preionized stage for FACET







n_p= 1×10^{17}cm^{-3}

N_{driver} = 2.9×10^{10}, σ_r= 3 m, σ_z = 30 m, Energy = 25 GeV

$N_{trailing}$ = 1.0×10^{10} , σ_r= 3 m , σ_z = 10 m, Energy = 25 GeV

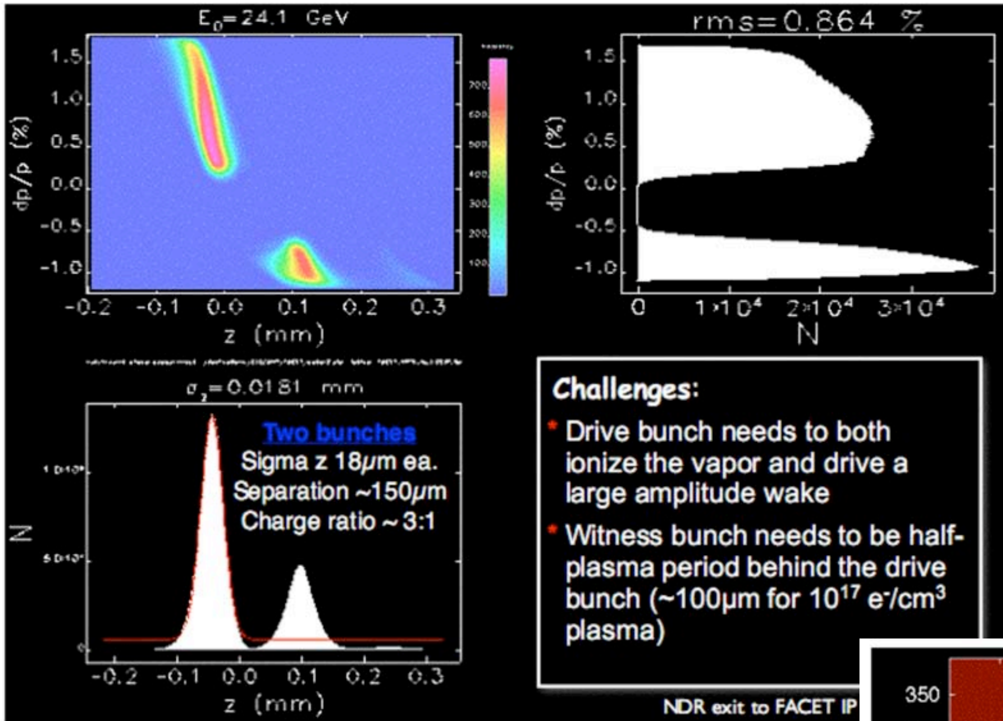
Spacing= 110 m

R_{trans} = -E_{acc}/E_{dec} > 1 (Energy gain exceeds 25 GeV per stage)

1% Energy spread

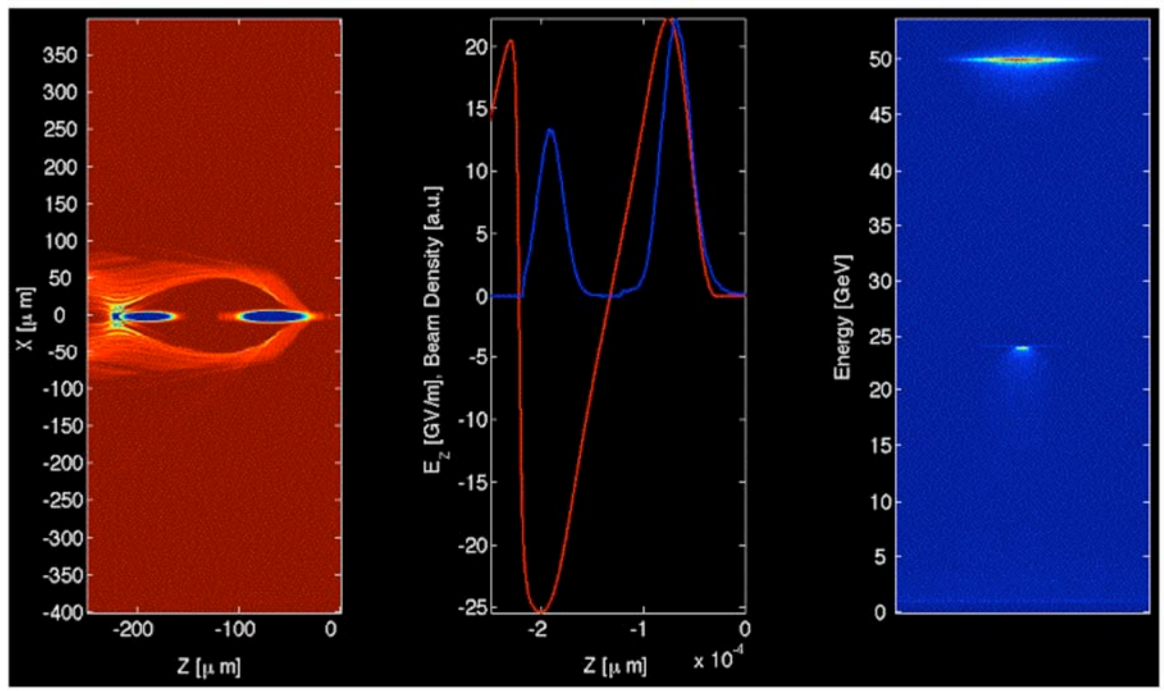
Efficiency from drive to trailing bunch ~48%!

Simulating 2-bunch experiment @ FACET



Two-bunch generation

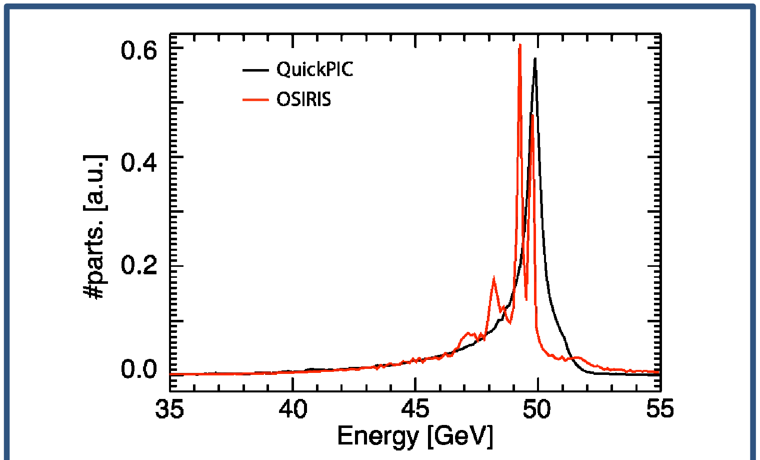
Possible FACET experimental parameters simulated in QuickPIC



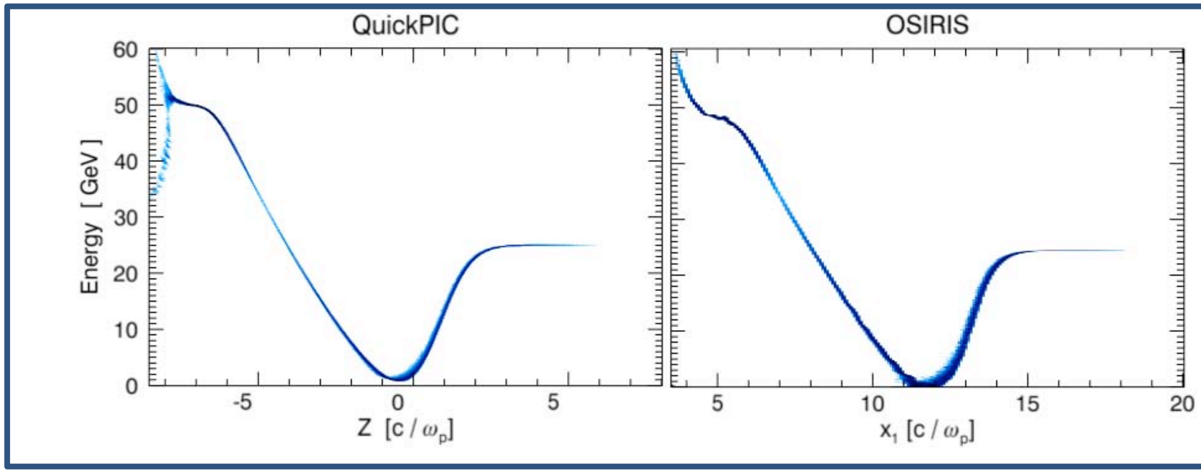
Comparison of OSIRIS 2D Cyl vs. QuickPIC with ionization over meter distances

Simulation of a nominal FACET stage

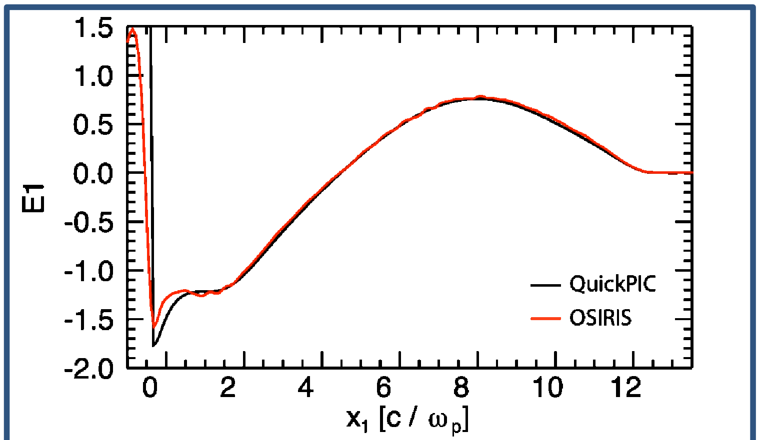
Energy spectrum :: Trailing beam



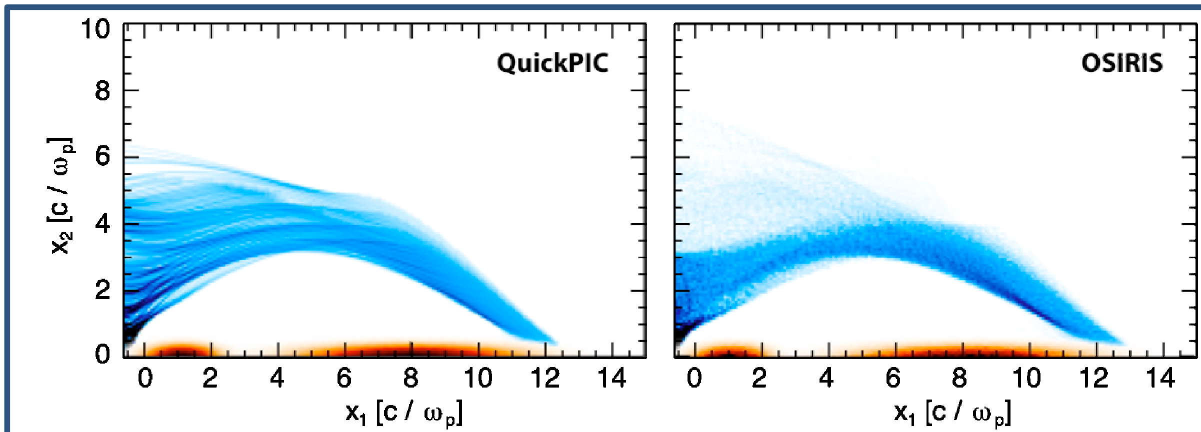
Phasespace :: Driving & Trailing beams



Accelerating field



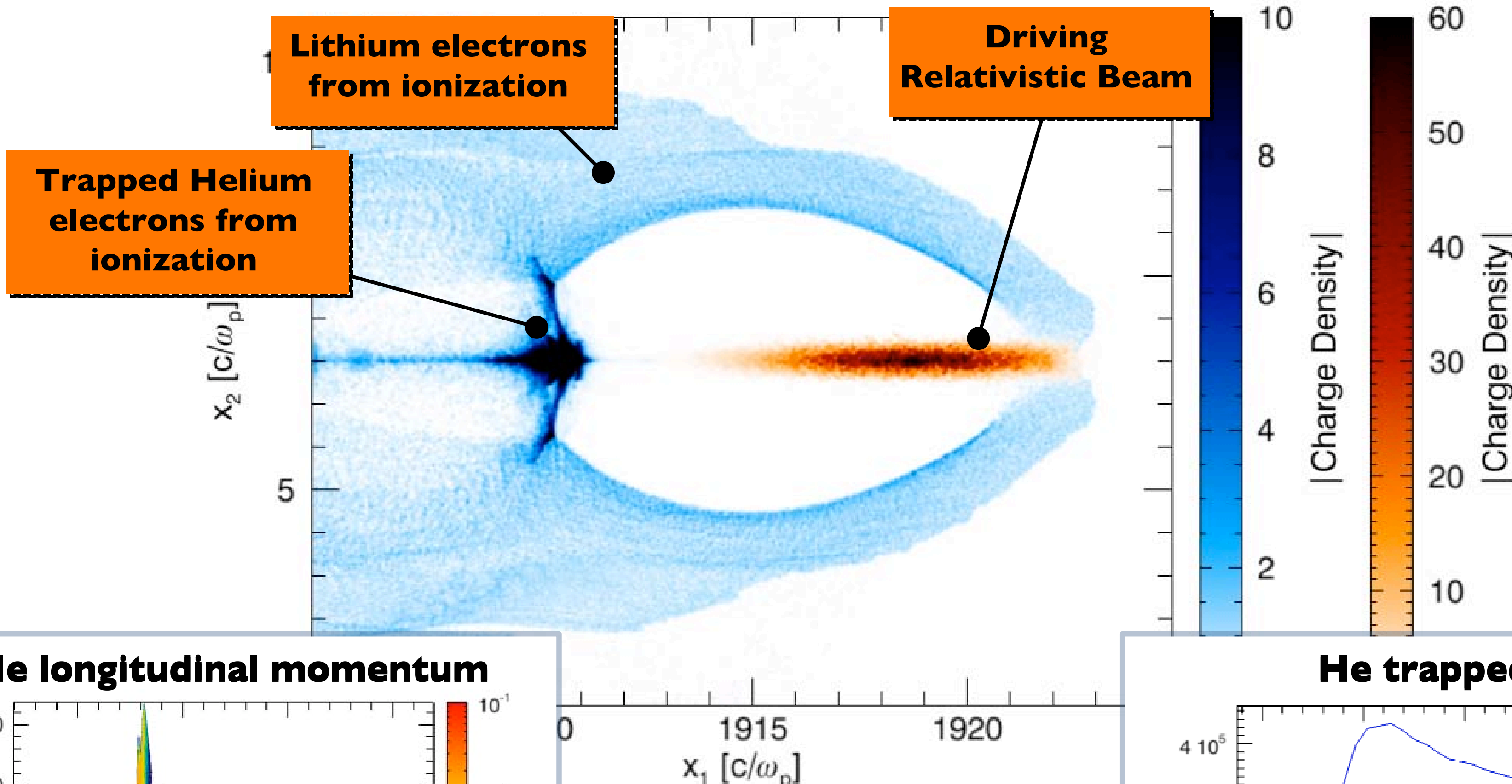
Charge density :: Lithium plasma + beams



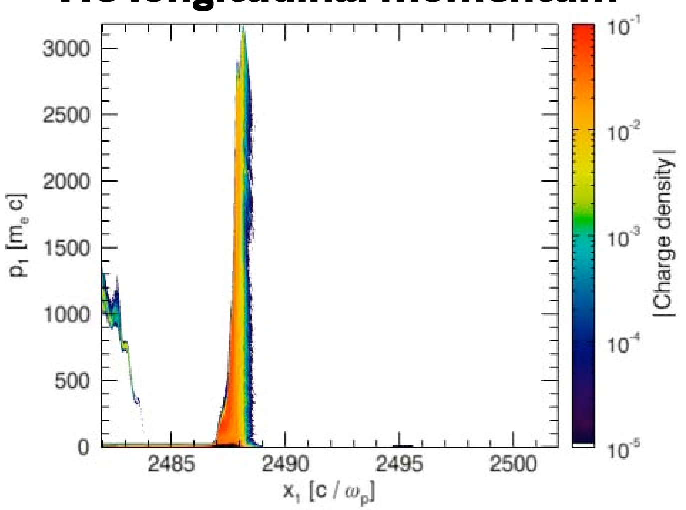
Computational Time [CPU.h]	**QuickPIC**	**OSIRS 2D Cyl**	**OSIRIS 3D** (estimate)
	~250	200	~50000

OSIRIS is used to model experiments:Ionization induced trapping with particle beams

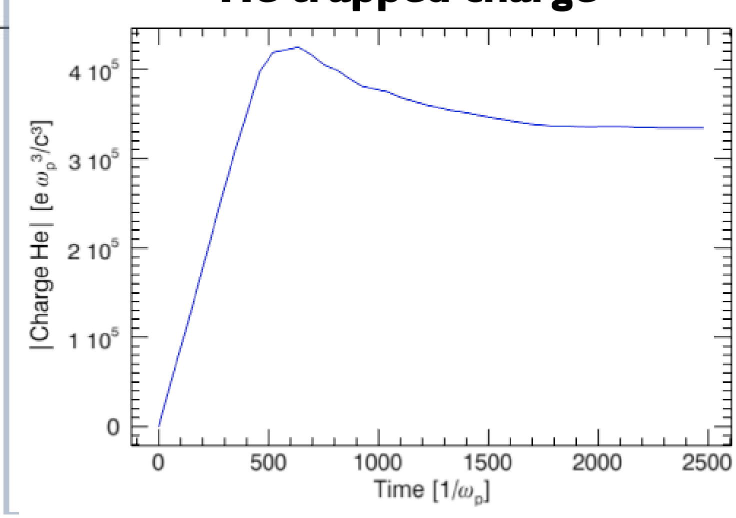
2D and 3D OSIRIS simulations in support of e-168 and FACET experiments



He longitudinal momentum



He trapped charge



PWFA-LC design exercise

- Focus on first/last PWFA stage
- Use theoretical framework to guide our designs
- Explore design options
- Test design with simulations

Why nonlinear physics is important ?

We start from:

$$\mathrm{n_b} = \frac{N}{(2\pi)^{3/2}\sigma_r^2\sigma_z}$$

High luminosity, beam loading efficiency requires $\mathrm{N} \sim 1\mathrm{x}10^{10}$

Emittance preservation requires matched beams:

$$\Rightarrow \sigma_r^2 = \sqrt{\frac{2}{\gamma}} k_p^{-1}\varepsilon_N^{-1}$$

In addition, in order to limit the energy spread:

$$\sigma_z \sim \alpha \frac{c}{\omega_p}$$

Therefore,

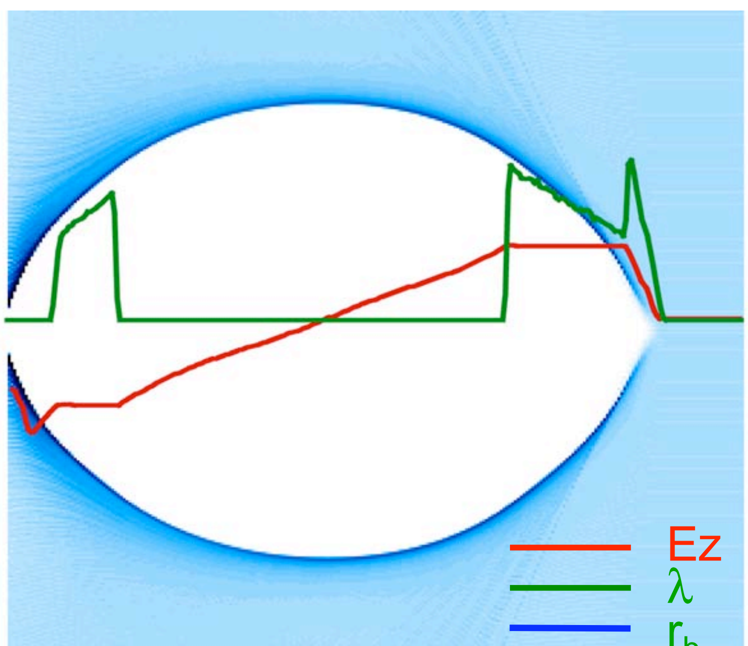
$$\frac{\mathrm{n_b}}{\mathrm{n_0}} = 7x10^3 \frac{N}{1x10^{10}} \frac{\mu m - rad}{\sqrt{\varepsilon_{Nx}\varepsilon_{Ny}}} \sqrt{\frac{Energy}{250GeV}} \frac{1}{\alpha}$$

Therefore, narrow beams which violate linear theory are required in the trailing beam for either PWFA or LWFA

PWFA-LC simulation design

To achieve the smallest energy spread of the beam, we want the beam-loaded wake to be flat within the beam.

Formulas for designing flat wakefield in blow-out regime (Lu et al., PRL 2006; Tzoufras et al, PRL 2008):



Simulation of the first and the last stages of a 19 stages 0.5TeV PWFA

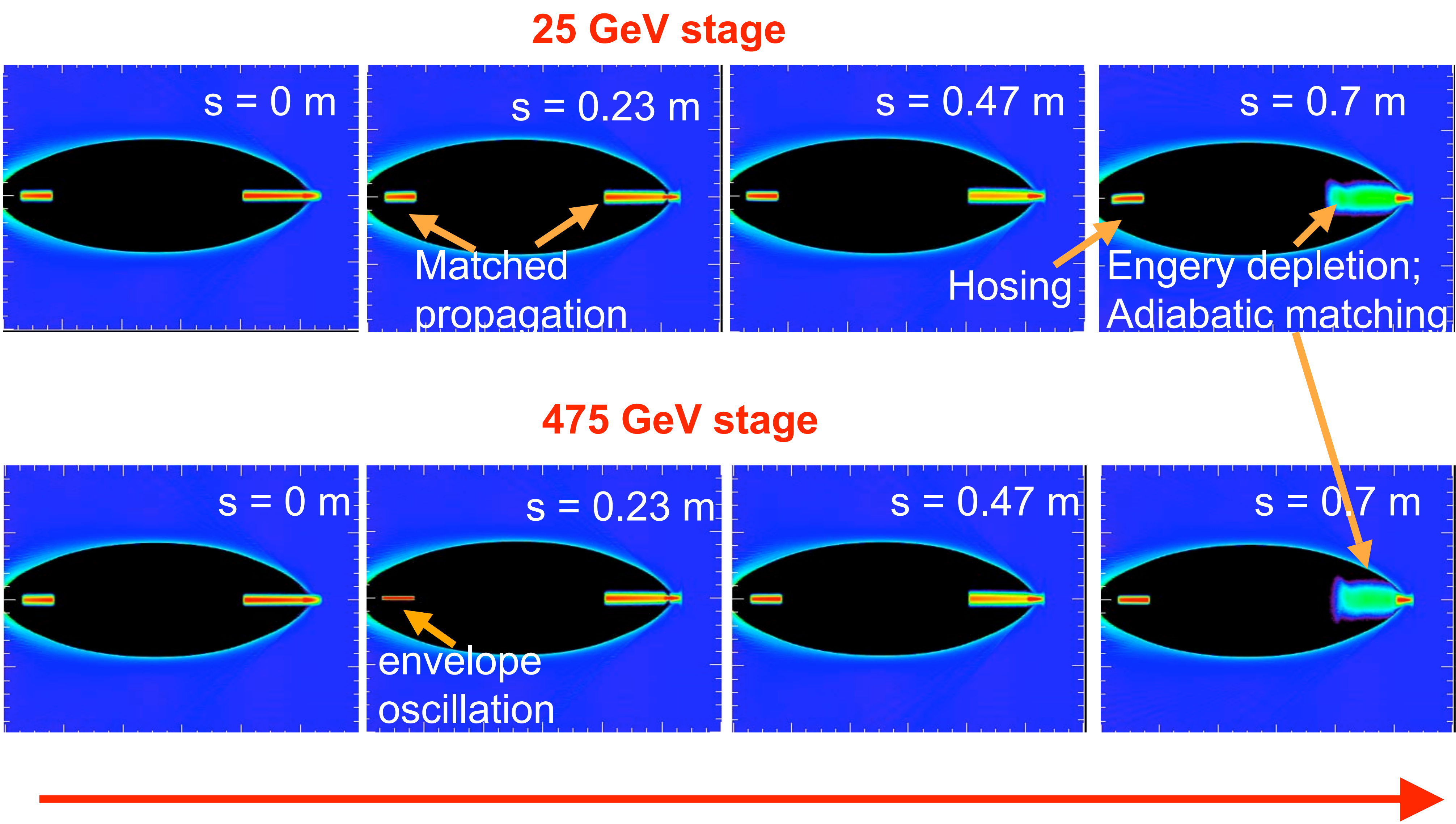
Physical Parameters

	Drive beam	Trailing beam
Beam Charge (1E10e^-)	0.82 + 3.65	1.62
Beam Length (micron)	13.4 + 44.7	22.35
Emittance (mm mrad)	10 / 62.9	62.9
Plasma density (1E16 cm^{-3})	5.66	
Plasma Length (m)	0.7	
Transformer ratio	1.2	
Loaded wake (GeV/m)	45 GeV/m	

Numerical Parameters

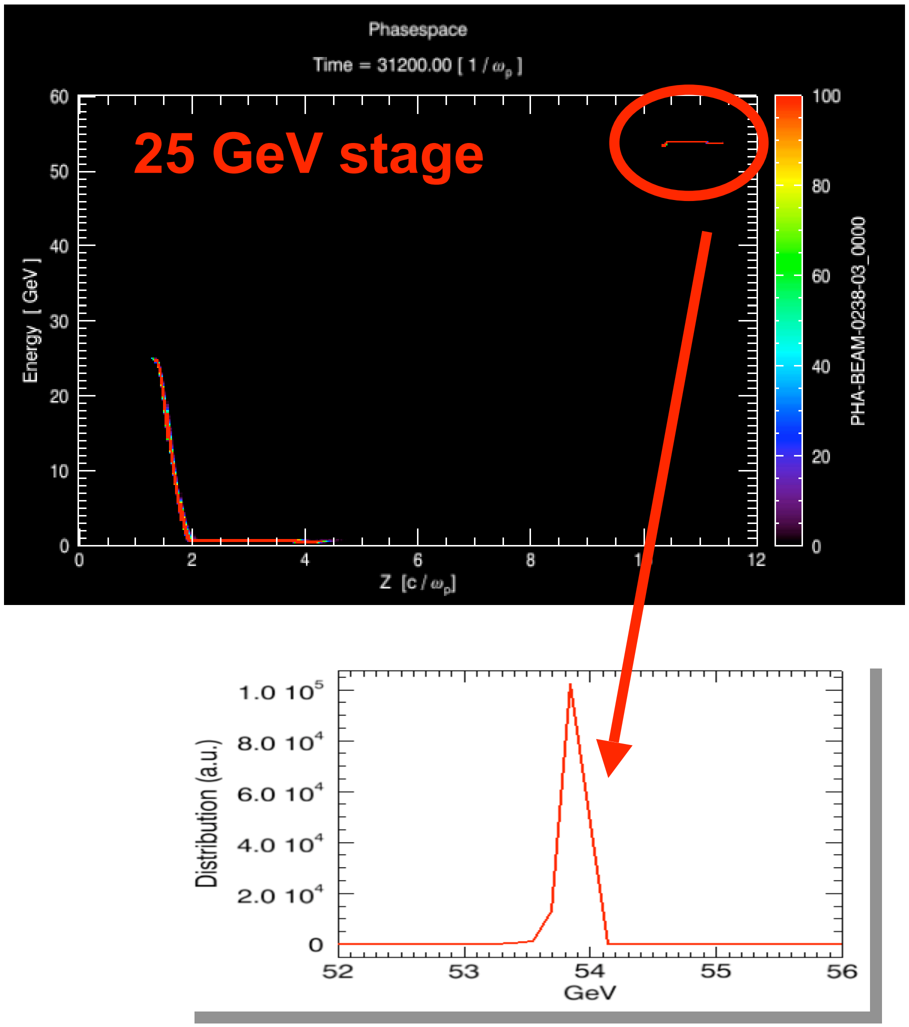
Box size	1000x1000x272
Grids	1024x1024x256
Plasma particle	4 / cell
Beam particle	8.4 E6 x 3
Time step	60 k_p^{-1}
Total step	520

QuickPIC simulations of 25/475 GeV stages

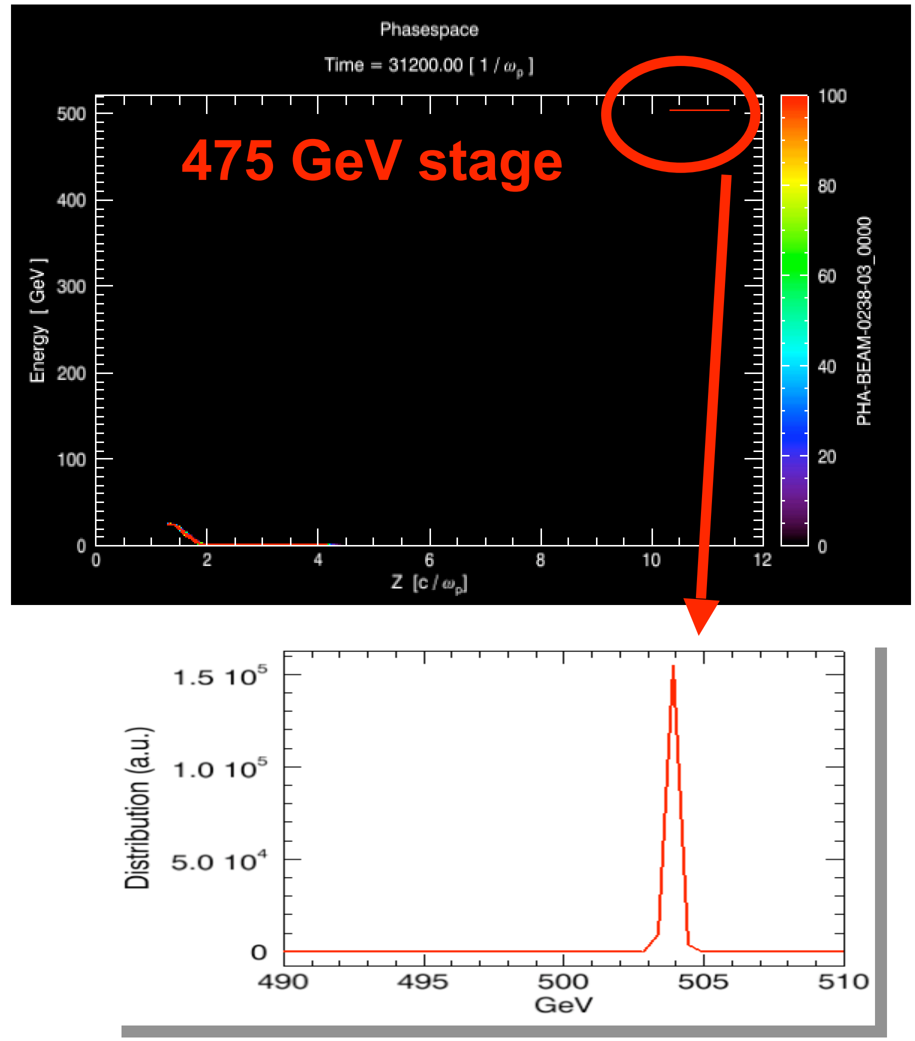


Simulations of 25/475 GeV stages

longitudinal phasespace



Energy spread = 0.7% (FWHM)



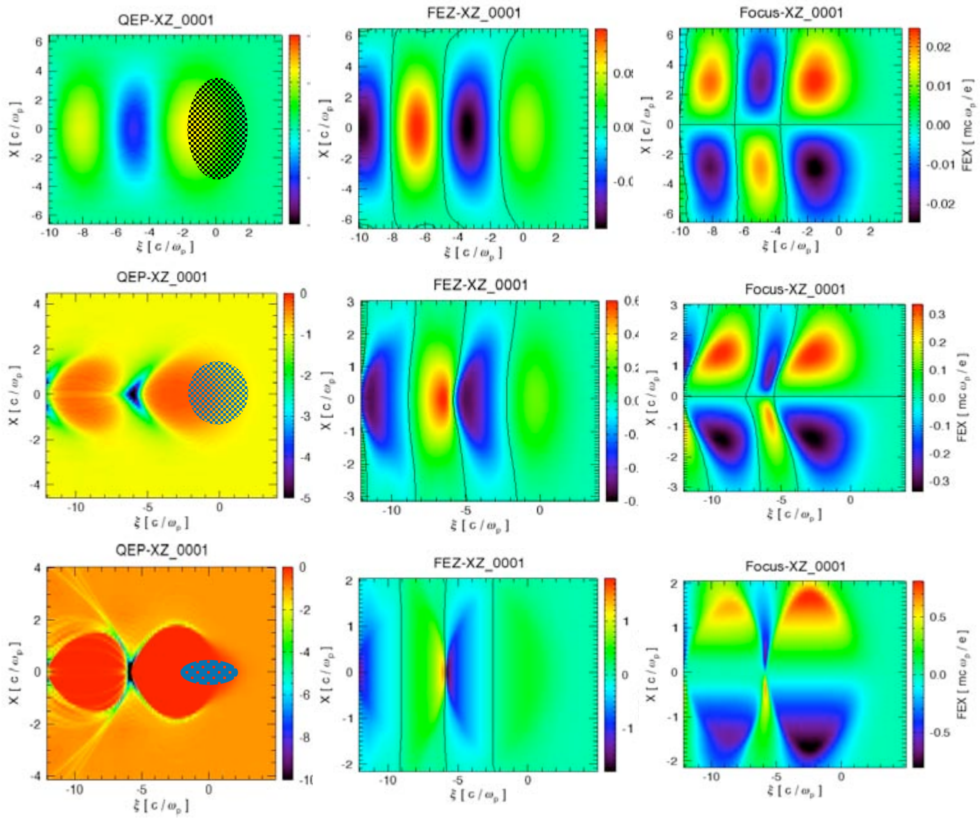
Energy spread = 0.2% (FWHM)

Positron acceleration in an electron beam-driven wake field

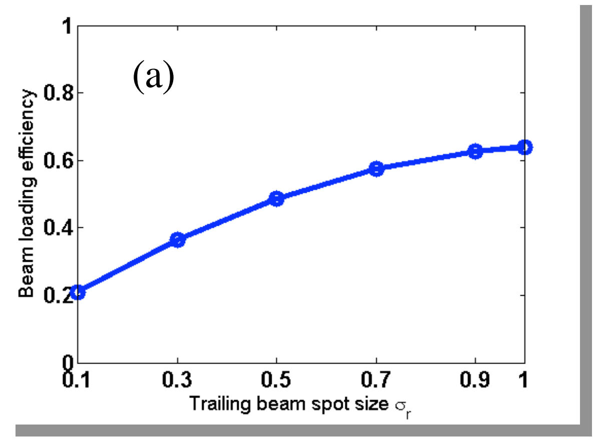
Linear Wake Field

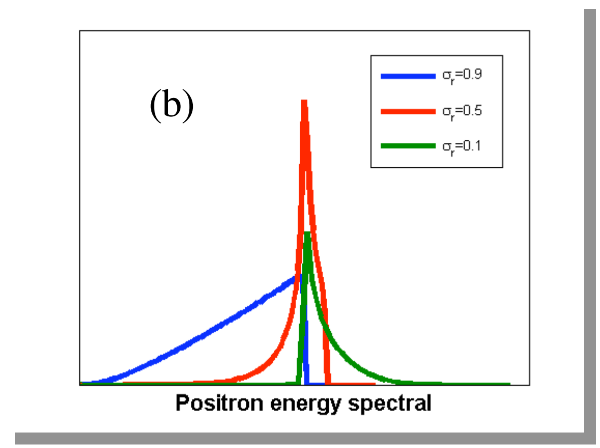
Weakly Nonlinear Wake Field

Ultra Nonlinear Wake Field



- Positron acceleration is not possible in an ultra nonlinear plasma wake field (the blow-out regime) due to the small focusing phase.
- The accelerating area for positron beam is outside the first period of the plasma wake field, which has been not sufficiently studied before.
- OSIRIS and QUICKPIC simulations are being used to study positron acceleration in linear and weakly nonlinear beam-driven plasma wake fields with the goal to find an optimal solution.





Positron (a) beam-loading efficiency and (b) energy spectrum with different spot sizes when accelerated in a linear plasma wake field

Synchrotron radiation & ion motion

Synchrontron Radiation

$$P_{loss} = \frac{2}{3}\frac{e^2}{c}\gamma^6\left(\left[\dot{\vec{\beta}}\right]^2 - \left[\vec{\beta}\times\dot{\vec{\beta}}\right]^2\right)$$

$$\frac{\varepsilon_r}{\varepsilon_{loaded}} = \frac{1}{\varepsilon_{loaded}} 1.5x10^{-5}\left(\frac{\mathrm{E}}{50GeV}\right)^2\left(\frac{n}{10^{16}}\right)^{3/2}\left(\frac{r}{1\mu m}\right)^2$$

For a matched beam this can be rewritten as:

$$\frac{\varepsilon_r}{\varepsilon_{loaded}} = \frac{1}{\varepsilon_{loaded}} 3.75x10^{-3}\left(\frac{\mathrm{E}}{250GeV}\right)^{3/2}\left(\frac{n}{10^{16}}\right)\left(\frac{\varepsilon_n}{10^{-6}m}\right)$$

Ion Motion

- Ion motion when

$$n_b > n_o \frac{M_i}{m_e}$$

- Matched beam spot size shrinks at large g, low ε_r

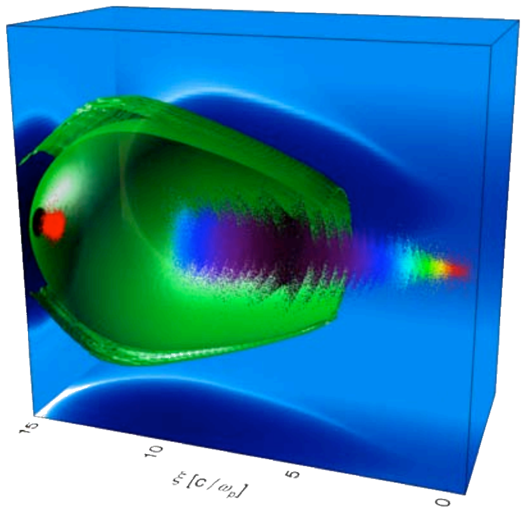
$$n_b \propto \sigma_x^{-1}\sigma_y^{-1} = \frac{1}{\sqrt{\varepsilon_{nx}\varepsilon_{ny}}}\sqrt{\frac{\gamma}{2}}\frac{\omega_p}{c}$$

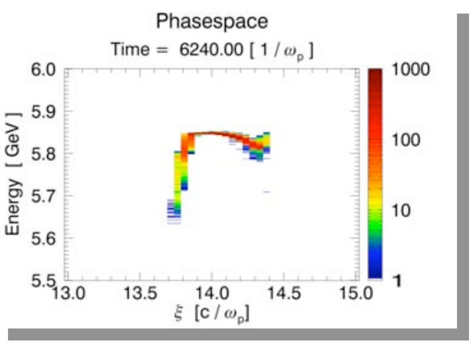
- For future collider
  - -e_{ny} down by 10^2 (e.g., 10nm-rad)
  - -g up by 10+
  - - n_b up by 10^2
  - -Ion motion must be included in design/models

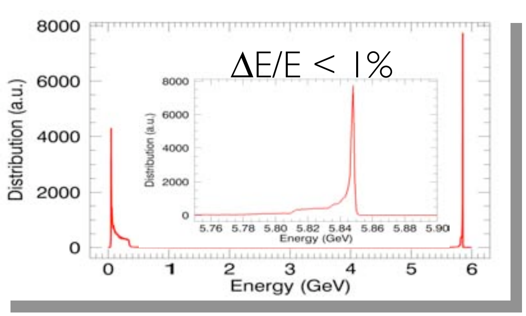
Ref.: S. Lee et al., AAC Proc (2000);
J. Rosenzweig et al., PRL (2006)

High Transformer Ratio PWFA: Application for LC and XFELs

- A high charge (5-10nC) low energy driver (1-3GeV) with an elongated current profile is used to drive a plasma wake in the blowout regime.
- An ultra-short high quality low charge beam (1nC) can be loaded into the wake at a proper phase and be accelerated to high energy (5-15GeV) in very short distance (10s of cms).
- The parameters needs to be optimized, such that high quality (0.1% energy spread and 1mm mrad emittance) and high efficiency (60-80%) can be simultaneously achieved

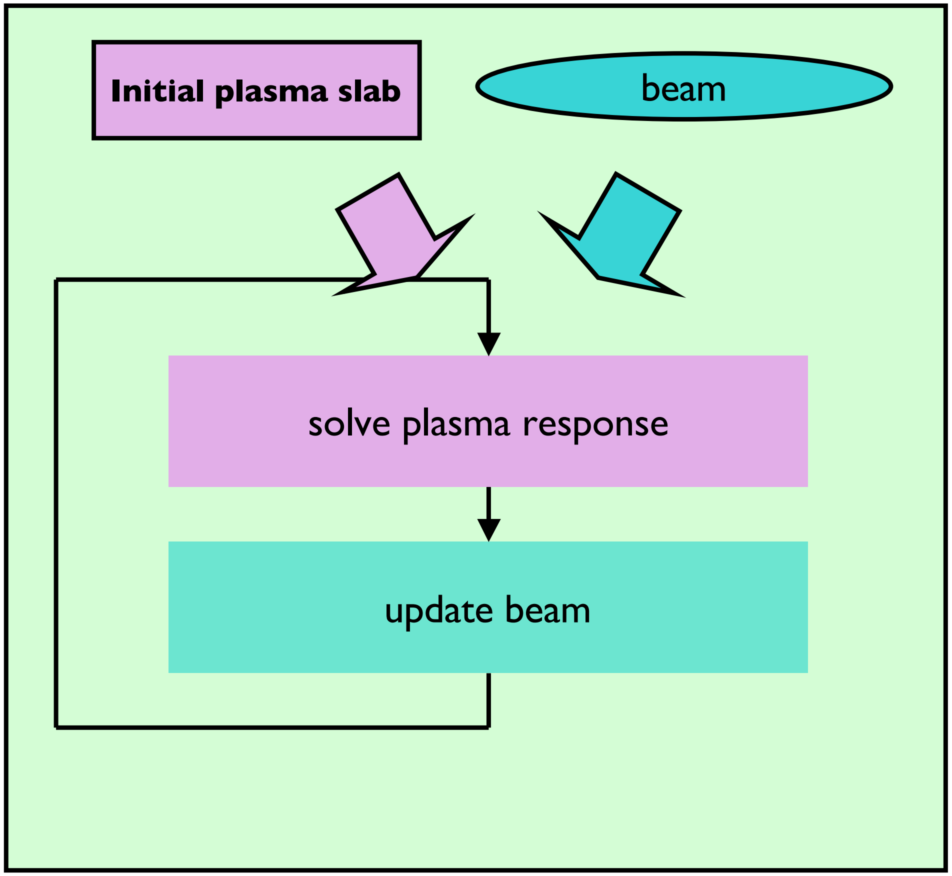


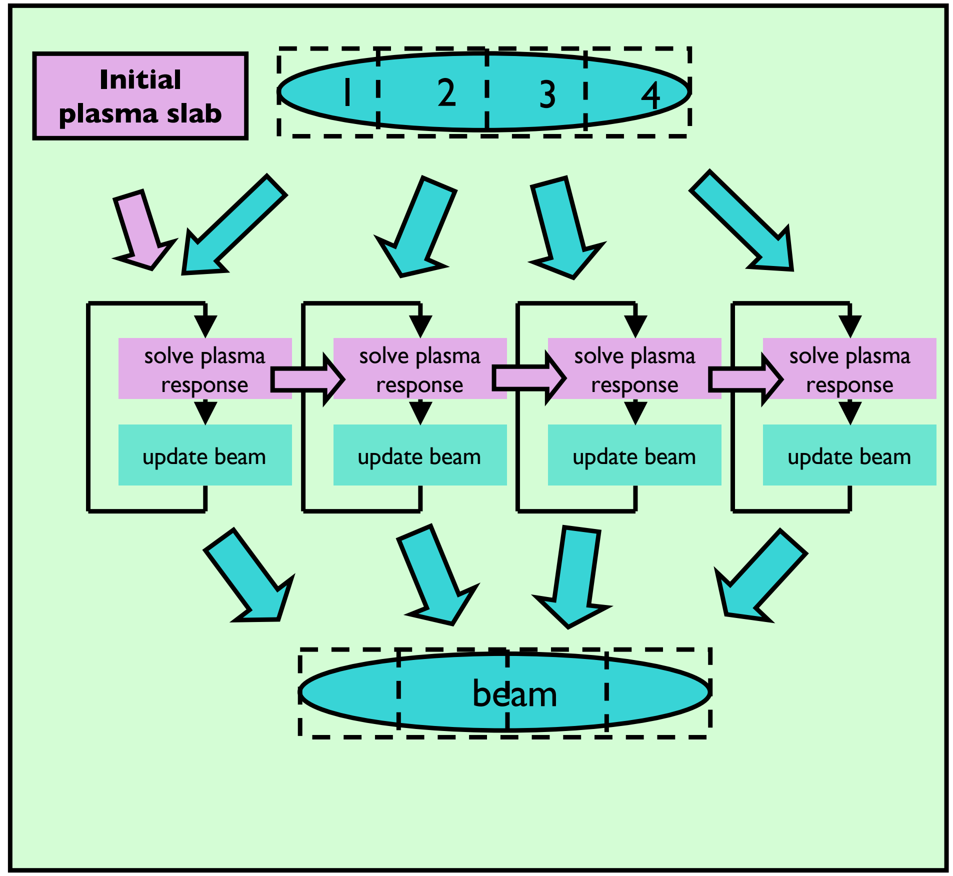




Physical parameters	
Drive beam	Charge = 3E10 (4.8 nC) Energy = 1GeV Length = 168 μm (0.56 ps) Transverse spot size = 5 μm Emittance = 1 mm mrad
Trailing beam	Charge = 0.22E10 (0.35 nC) Energy = 1GeV Length = 7 μm (23 fs) Transverse spot size = 5 μm Emittance = 1 mm mrad
Plasma	Density (edge) = 1E17 cm^{-3} Density (center) = 0.5E17 cm^{-3} Channel radius = 68 μm Length = 10.8 cm

Scaling to 100,000+ processors and high resolution capability:Pipeling

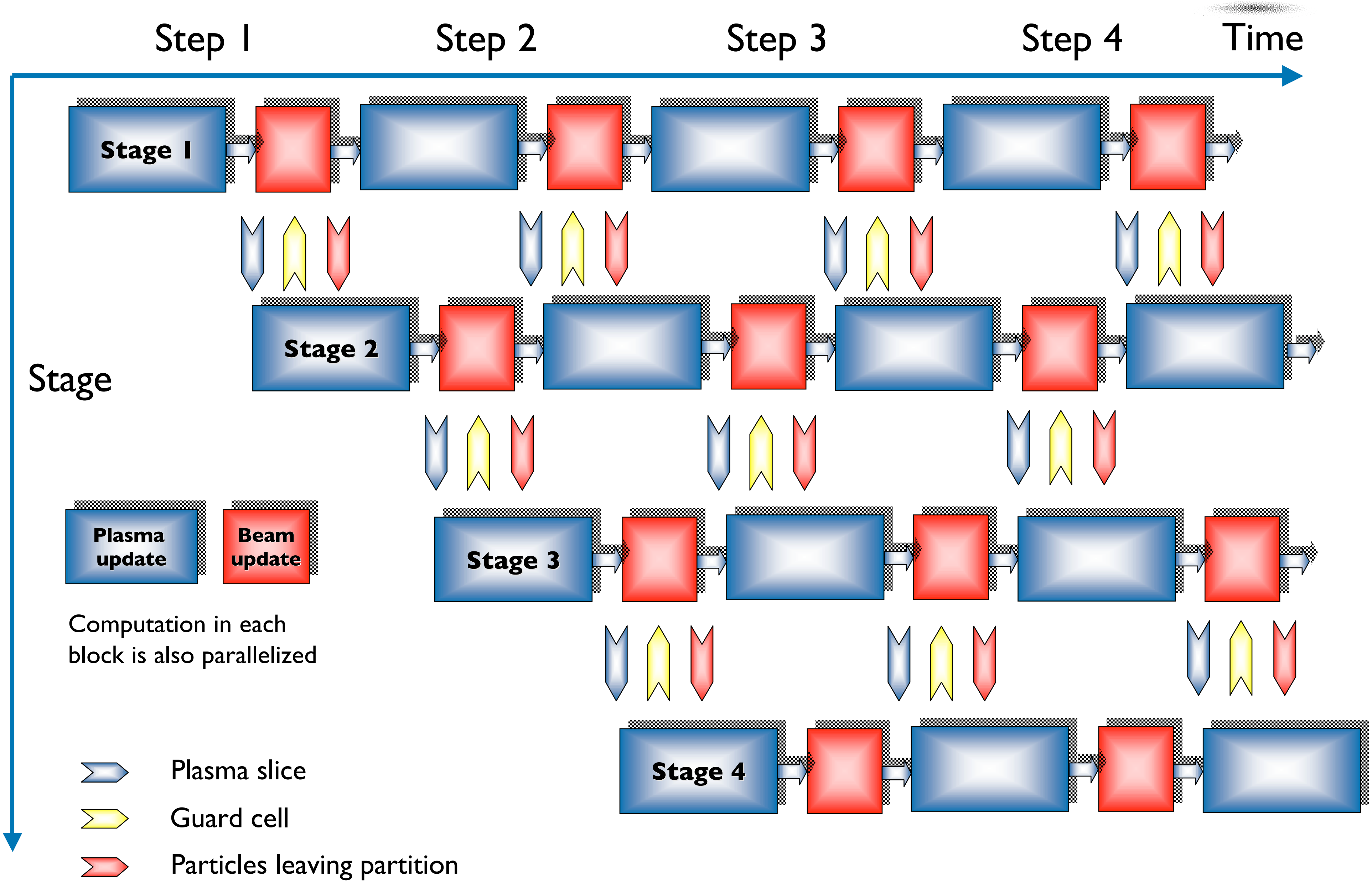




Without pipelining: Beam (particles or laser) is not advanced until entire plasma response is determined

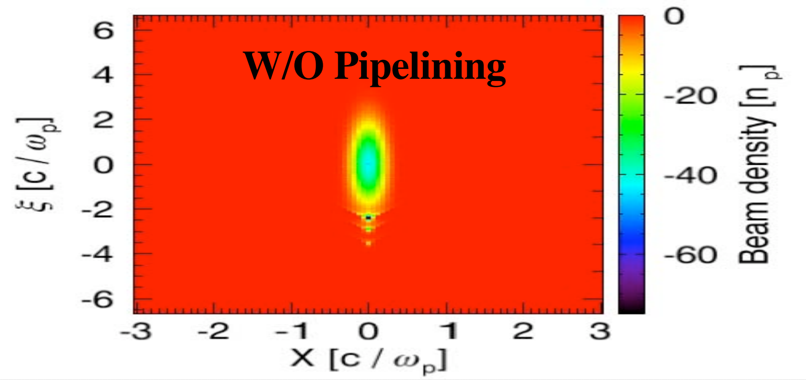
With pipelining: Each section is updated when its input is ready, the plasma slab flows in the pipeline.

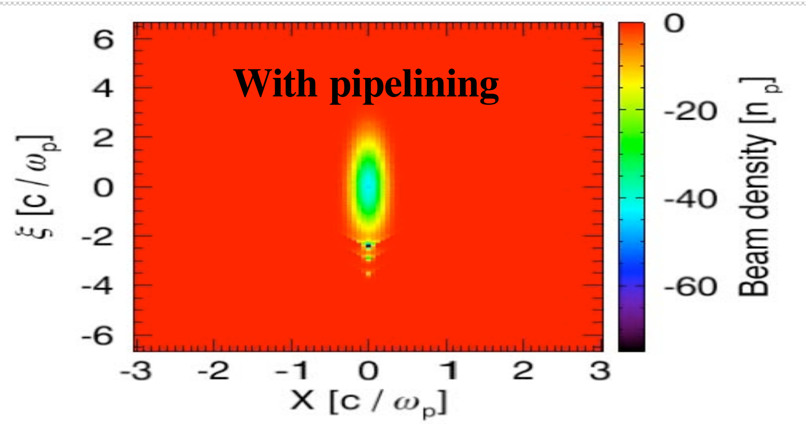
Pipelining : A closer look

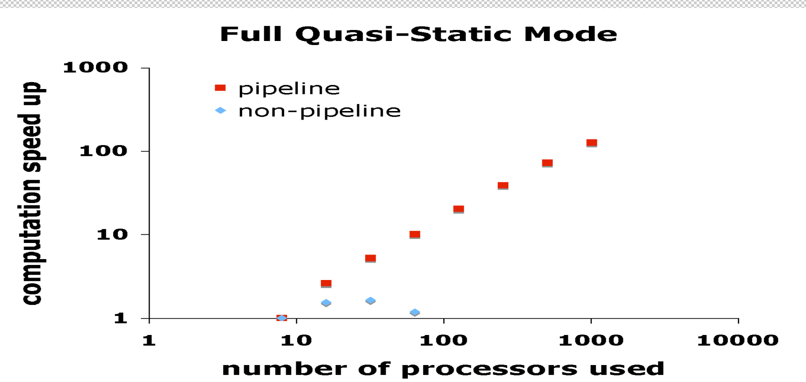


Pipeline algorithm verification and scaling

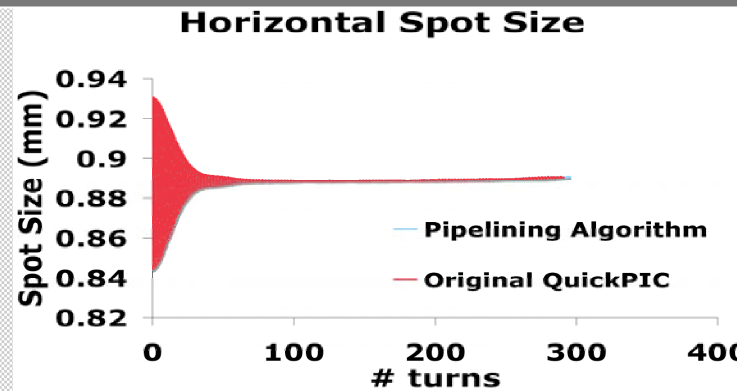
PWFA simulation

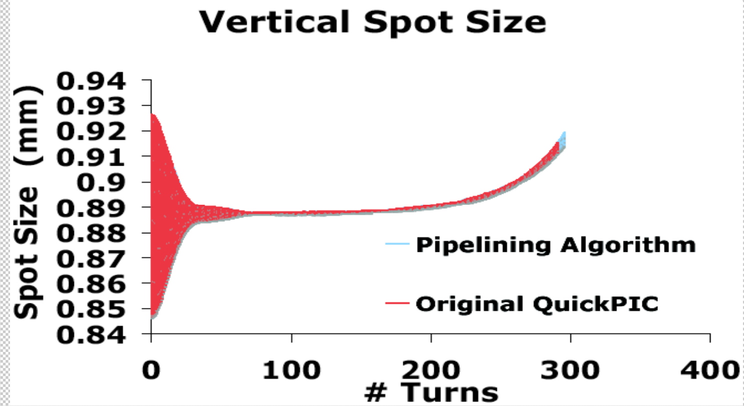


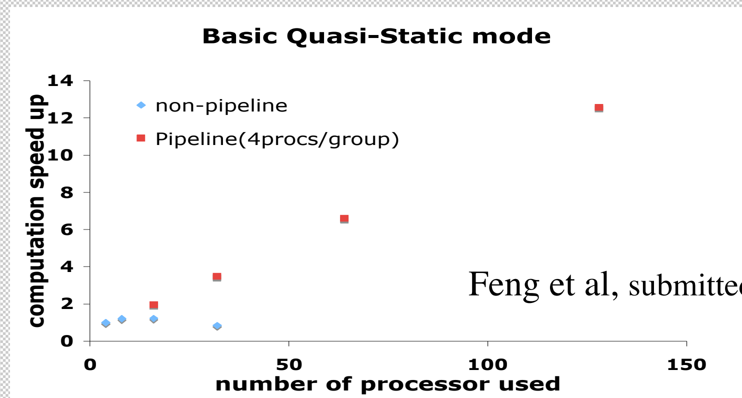




E-cloud simulation







Feng et al, submitted to JCP

Enhancing pipeline operation: enabling high resolution

Work in progress & Future improvement

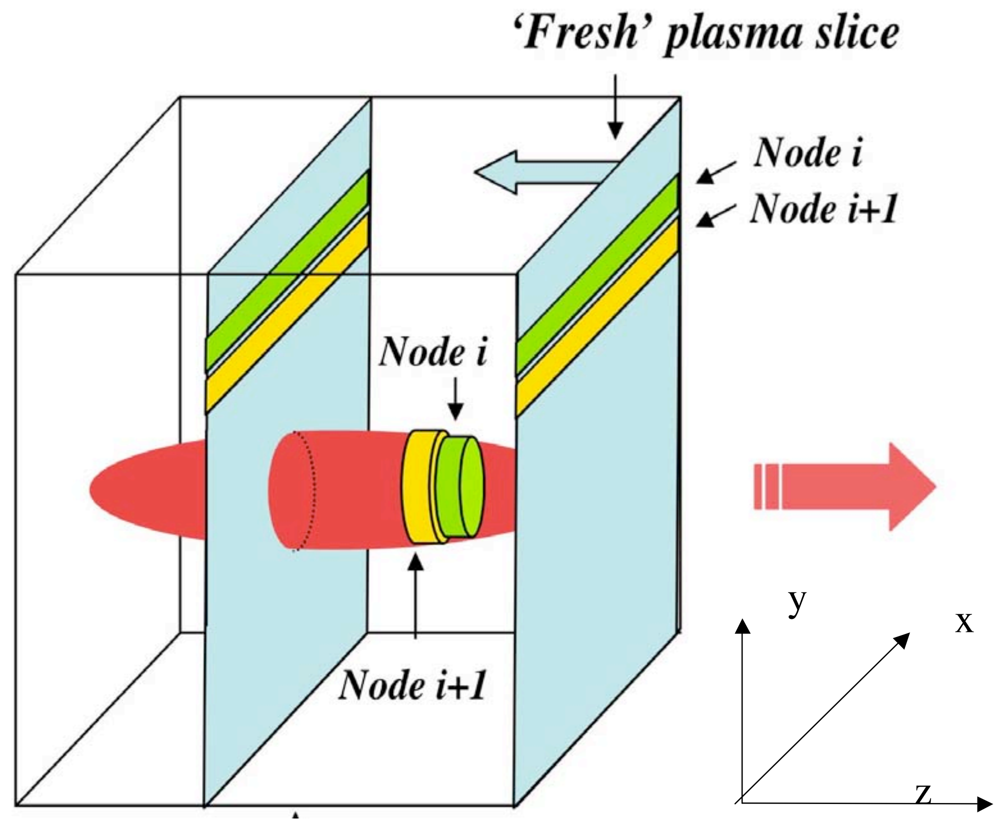
- Enhanced domain decomposition (in Z and in Y, or 2D decomposition). Enables the use of more processors in the transverse direction and extremely fine resolution which is required for simulating narrow trailing beams in PWFA-LC.

- For small pipeline stage, 3D beam update should be load balanced.

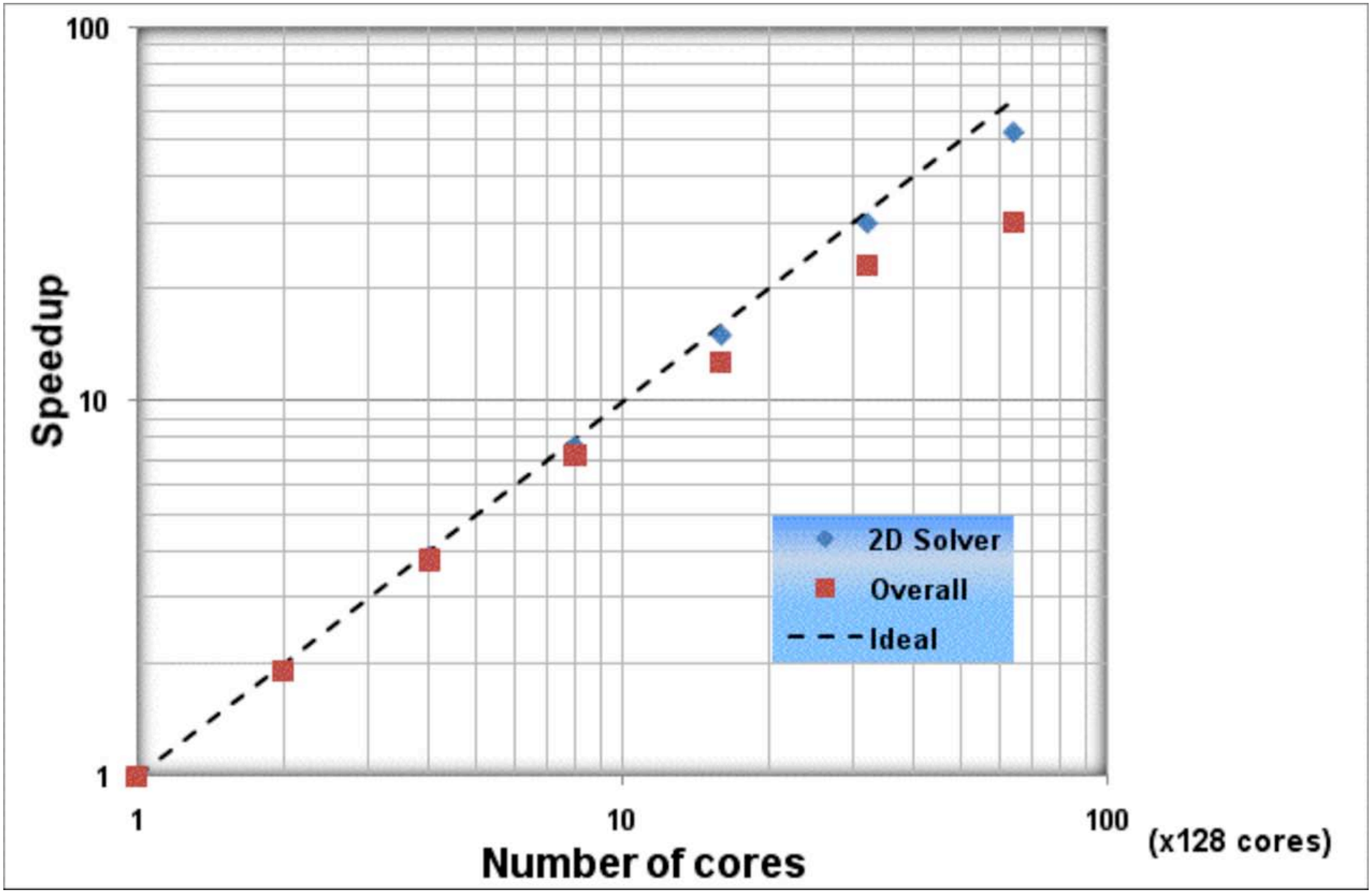
  For example, 16 pipeline stages,

  2D: 1102.8 sec / 79.4 sec = 13.9 times faster

  3D: 15.5 sec / 2.2 sec = 7.04



Preliminary parallel scaling on Franklin



Summary

•PWFA physics and experiments are modeled through a combination of quasi-static and full PIC simulations.

•PWFA experiments have shown sustained acceleration of electrons over meter-long plasma. Quasi-static modeling enables 3D full-scale simulations that reveal the underlying physics.

•Simulations of two beam PWFA experiments at the proposed FACET facility shows that a high quality beam can be accelerated while maintaining beam quality.

•Simulations were conducted to explore the possibility of a 19 stages PWFA-LC, and to explore positron acceleration in the wake of an electron beam.

•Designing PWFA-LC for a TeV collider scenario is challenging. Modeling tools which include all the relevant physics such as beam-loading, hosing, head erosion, ion motion, and radiation loss are needed. Theoretical understanding of the blow-out regime and beam-loading make it possible to reduce energy spread of the accelerated beam and improve the overall efficiency.

•QuickPIC and OSIRIS continue to be enhanced. QuickPIC is being scaled to 10,000+ processors by developing a pipelining routine with multi-dimensional decomposition. This will also permit sub micron resolution for the transverse beam sizes.

•We would also like to add pipelining for the laser solver for enhanced LWFA simulations and to improve the convergence of the iterative solver for fields and particles.

Basic parameters

In the blow-out regime:

Dimensionless beam current:

$$\Lambda = k_p^2 \sigma_r^2 n_b / n_p = 2I_{peak} / I_A \ (for\ gaussian$$
$$beam;\ for\ round\ beam,\ r_b = \sigma_r / \sqrt{2})$$
$$I_A = mc^3/e = 17kA \ \ (Alfven\ current, 3.5\times10^8 e/\mu m)$$

Size:

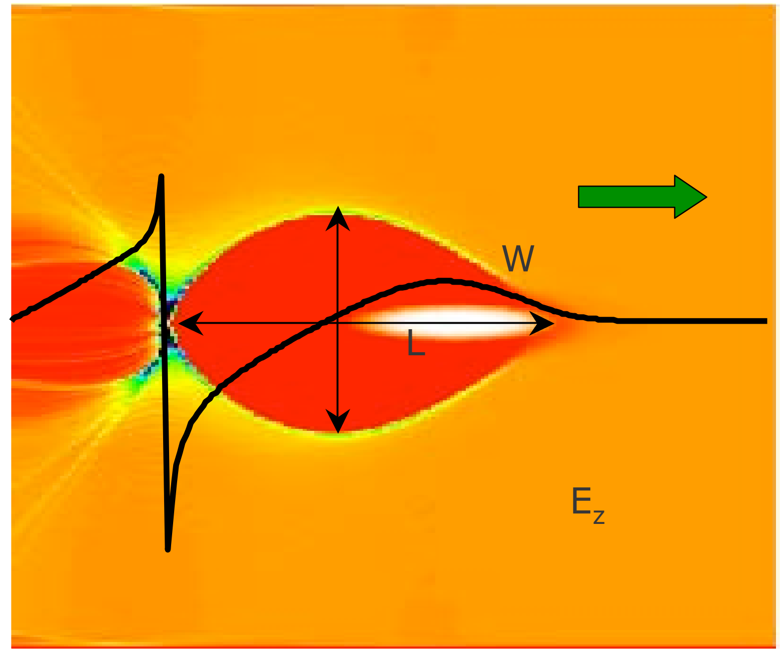
$$L \propto n_p^{-1/2}$$
$$W \propto \sqrt{\Lambda}\cdot k_p^{-1} = \sqrt{\sigma_r^2 n_b / n_p}$$

Accel. Gradient:

$$E_z = 1.3\Lambda \ln\left(\frac{10}{\Lambda}\right)^{1/2} \times \frac{mc\omega_p}{e}$$

Accel. Length:

$$s = \gamma k_p^{-1} \ \ or\ k_\beta s = \frac{\gamma}{\sqrt{2\gamma}} = \sqrt{\frac{\gamma}{2}}$$



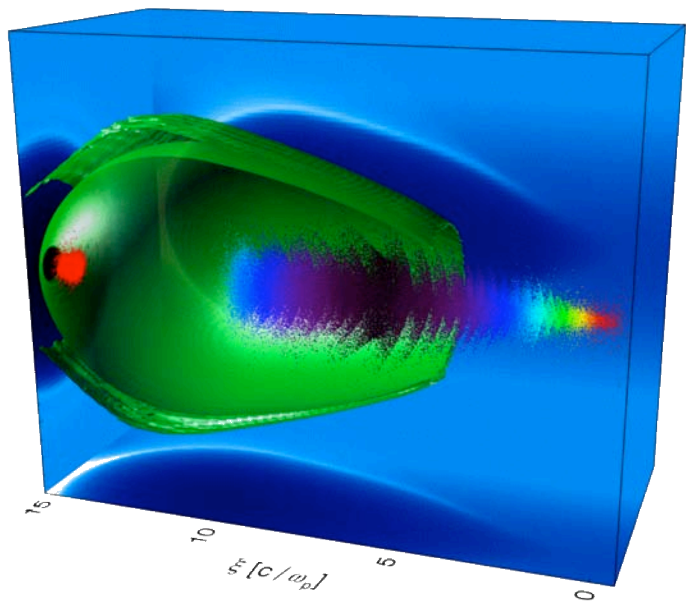
Practical parameters:
Beam : ~1E10 e$^-$
Plasma : 1E14 cm^{-3} ~ 1E18 cm^{-3}
(Ez = 1~100 GeV/m)

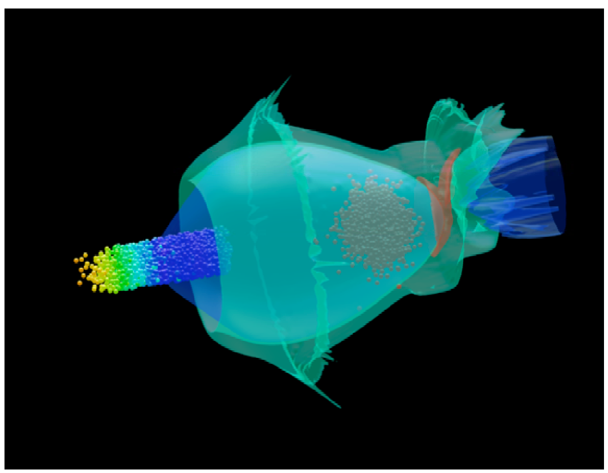
To blow-out (W/2=1~3), bunch length 3 ~ 30 micron

Quasi-Static PIC codes for large scale modeling

QuickPIC

- Massivelly Parallel, 3D Quasi-static particle-in-cell code
- Ponderomotive guiding center for laser driver
- 100-1000+ savings with high fidelity
- Field ionization and radiation reaction included
- Simplified version used for e-cloud modeling
- Developed by the UCLA+UMaryland+IST:





New Features

- Particle tracking
- Pipelining
- Parallel scaling to 1,000+ processors
- Enhanced Pipelining algorithm under testing, enabling scaling to 10,000+ processors and unprecedented simulation resolution down to nm

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